

Computations of high enthalpy shock-waves in EAST using US3D



DURGESH CHANDEL

University of Minnesota

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Entry Systems and Technology Division
NASA Ames Research Center

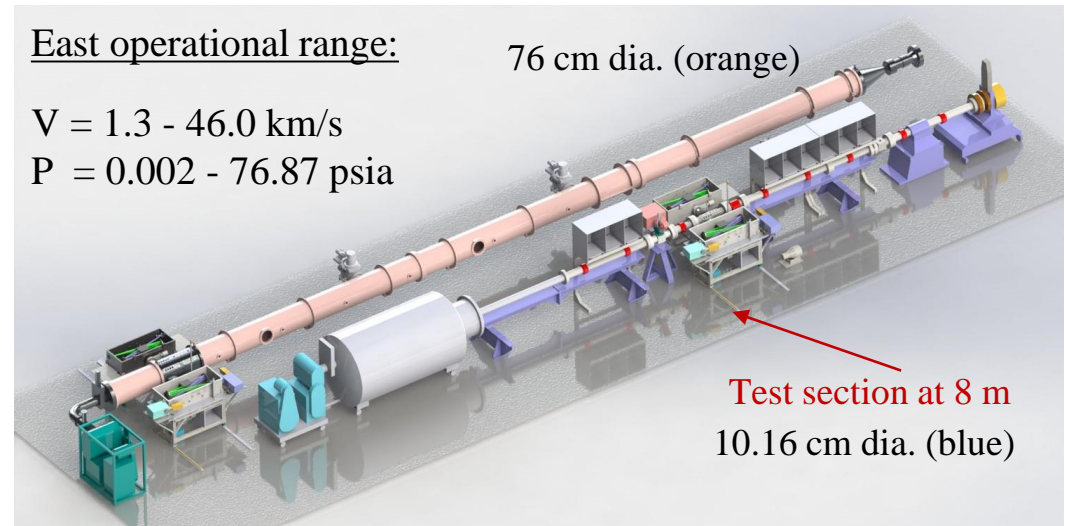
Motivation



- High-speed entry vehicles experience immense surface-heating and ablation.
- Radiative heating is important, requires knowledge of gas-state and reaction kinetics.



all images from nasa.gov



Shock-tube experiments inform about,

- Spectroscopic and Kinetics models
- Validation and uncertainty quantification for flight data

Typical conditions:

$M = 23-32$

$V = 8-12 \text{ km/s}$

$P = 3.87 \times 10^{-3} \text{ psia}$

$h_0 = 33-60 \text{ MJ/kg}$

High-fidelity computations are required to interpret EAST data.

EAST flow

- Current interpretation: Flow over blunt-body
- Previous attempts
- Improved approach in US3D

Fluid Solver results

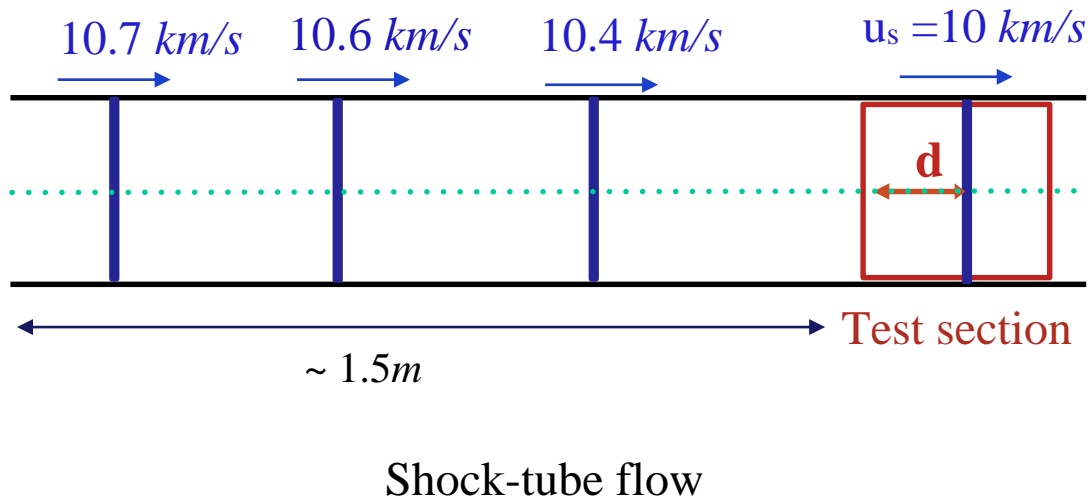
- Early evolution of shock
- Set-up for Radiation Calculations

Radiation solver results

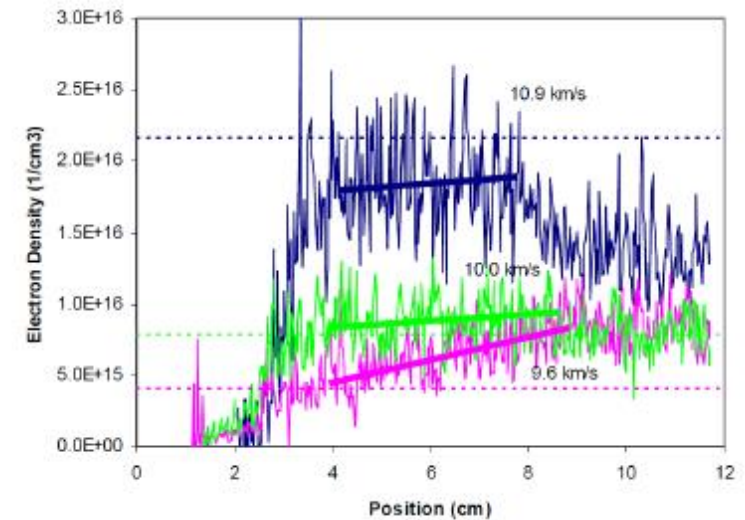
Summary and Path forward

EAST: Flow over blunt-body

- Stagnation streamline analogous to shock-tube centerline.
- Shock-speed is matched with an appropriately chosen shock stand-off distance.



Air-shocks

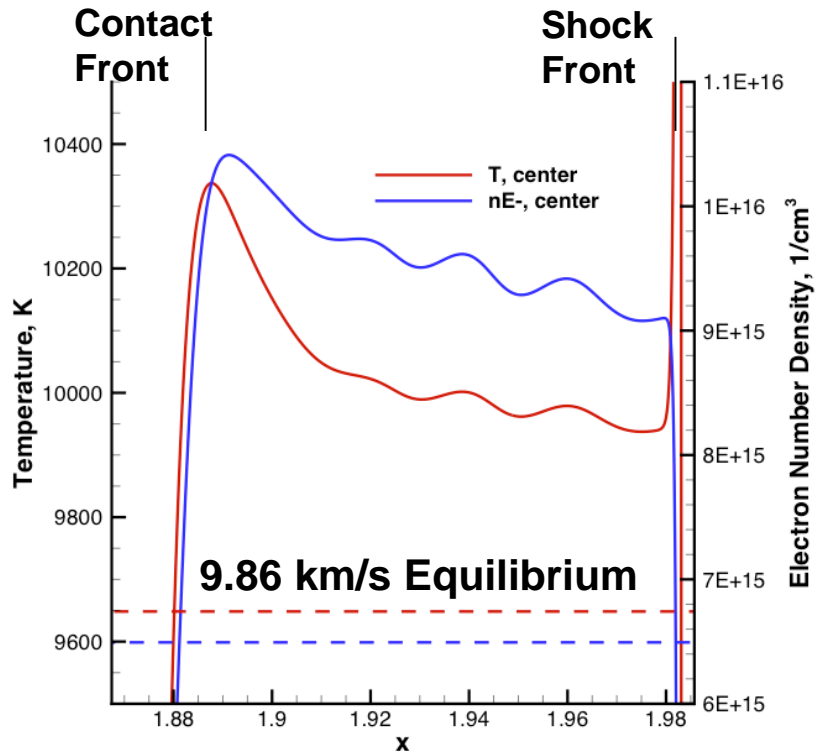


- Shock-deceleration and varied shock-strength causes strong non-equilibrium.
- Experimental data deviates from numerical predictions at certain conditions.

EAST: Previous Attempts

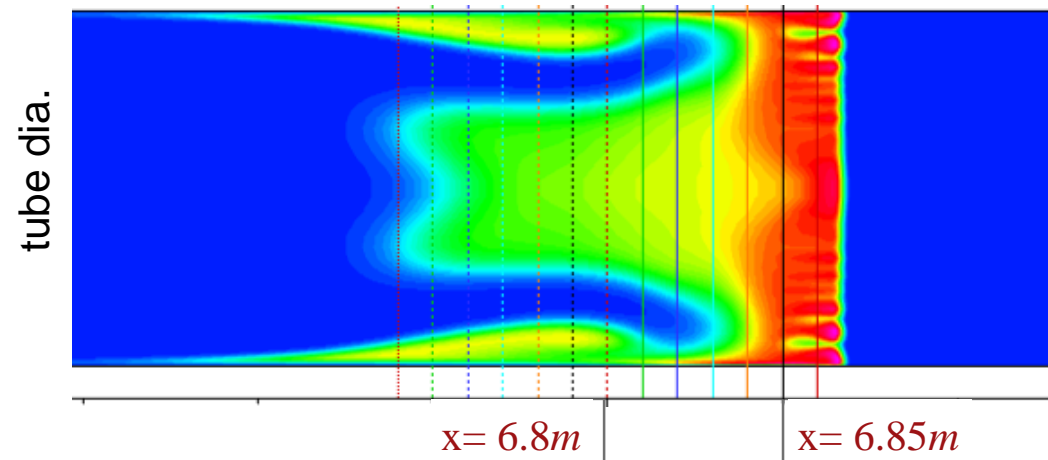


- Kotov et al. (*JCP* 2014), 1T model, 2D duct
- Low-dissipation, high order shock-capturing



Contact-front lacks thermal equilibrium
7 days for 2m shock-travel on 2000 CPUs

- Barnhardt et al., attempted full facility DPLR simulation, 2009
- Aggressive CFL ramping caused instability



Ionization-fraction, near Test-section

Radiance monotonically decreases behind shock.

Lower CFL cases in DPLR also get unstable.
COOLFluid simulations are stable but expensive
(Bensassi, K.)

Time-accurate EAST simulations are expensive.

EAST: Improved Approach in US3D



Goal: 2D axi-symmetric flow simulations w/ real-gas effects.
(time-accurate yet computationally feasible!)

Required modifications:

- Implicit system of equations needs higher accuracy than stagnant shock-problems.
(more 'kmax' sub-iterations in computing Flux-Jacobians in each time-step)
- Catalytic recombination BC at wall
- Moving Grid and/or Numerical interpolation introduces errors.
- Moving frame-of reference? Frame-acceleration requires additional modeling.

Moving-frame w/ constant frame-speed:

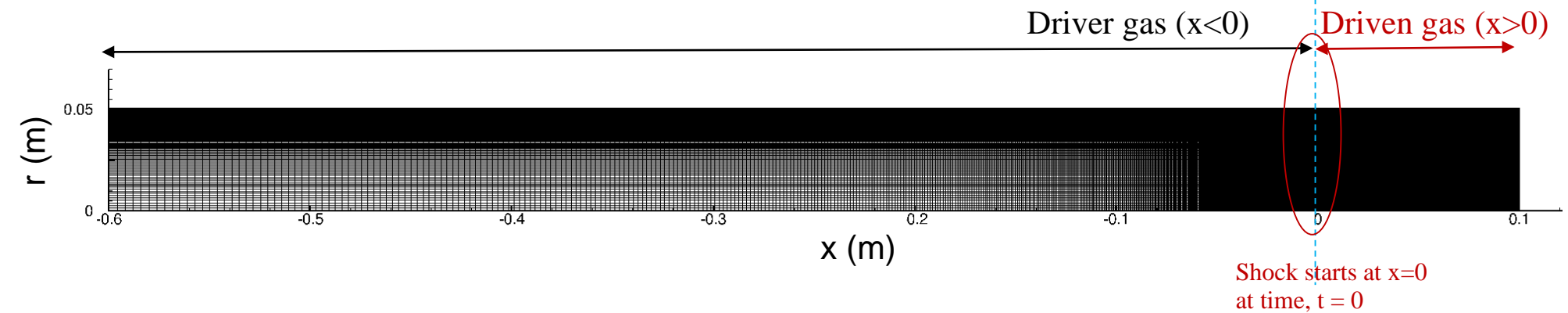
1. US3D code is heavily tested and verified for stagnant bow-shock problems.
2. Shock-frame calc. found to be more accurate than Lab-frame calc.
(moving-shock in perfect gas at $M = 3, 5, 14$)
3. Standing shock simulations at $M = 20$ keep the shock stagnant as expected.

Shock-frame is the best framework for moving-shock problems in US3D.

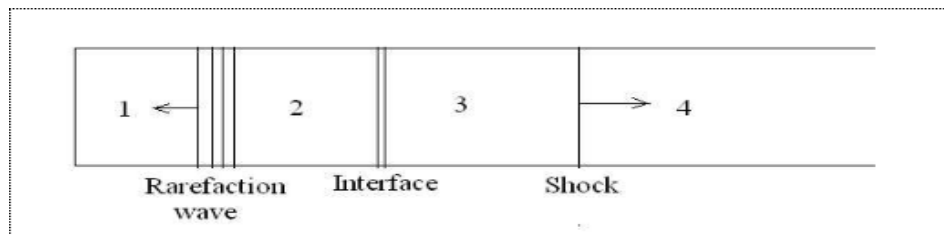
Numerical set-up: Shock-frame calc.

<i>Flux scheme</i>	1 st order MSW
<i>Time-integration</i>	1 st order implicit FMDP
<i>Frame-of-reference</i>	Shock-frame
<i>Grid size</i>	Variable grid, 1.8 M
<i>Grid resolution (min.)</i>	$\Delta x = 10 \mu\text{m}$ near shock $\Delta r = 1 \mu\text{m}$ near wall

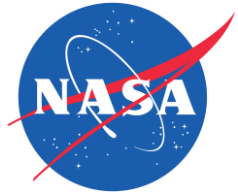
99.9% He + N ₂	79% N ₂ + O ₂
1.10546 kg/m ³	3.096d-04 kg/m ³
6000 K	300 K



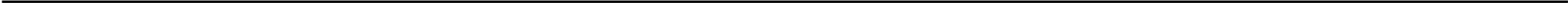
Wave motion in shock tube at time $t > 0$



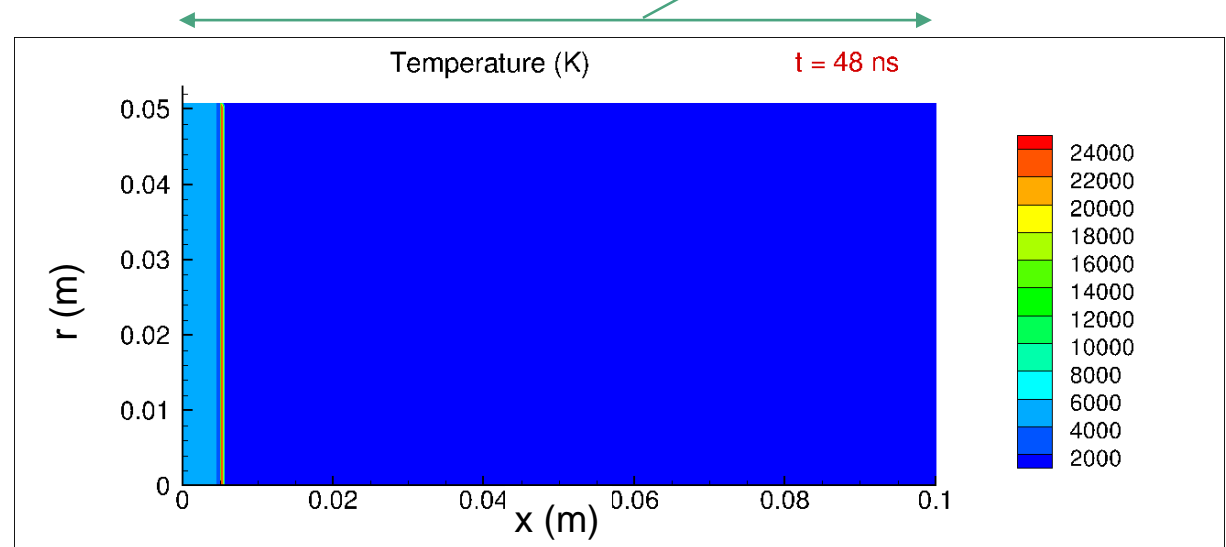
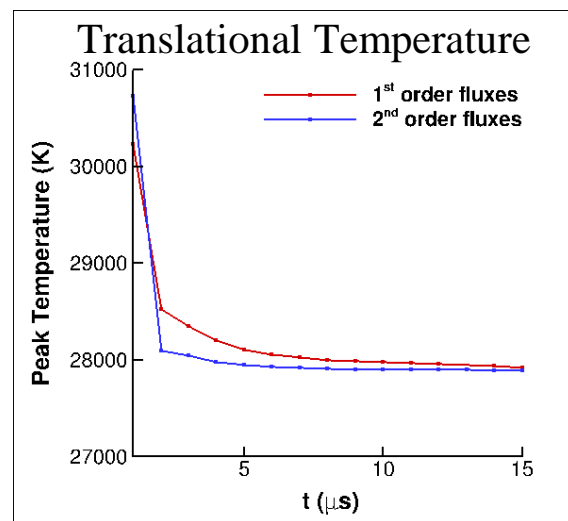
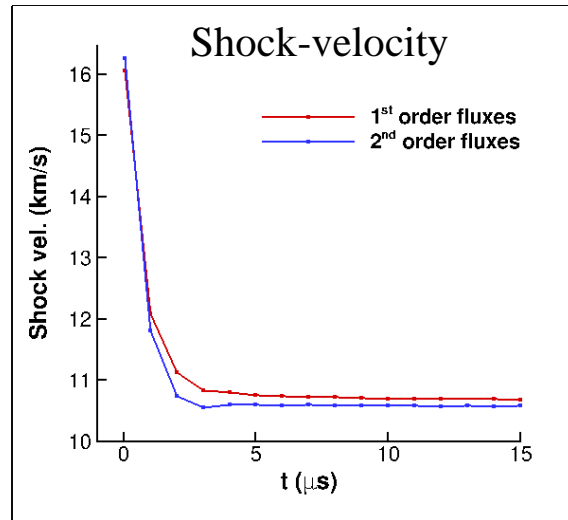
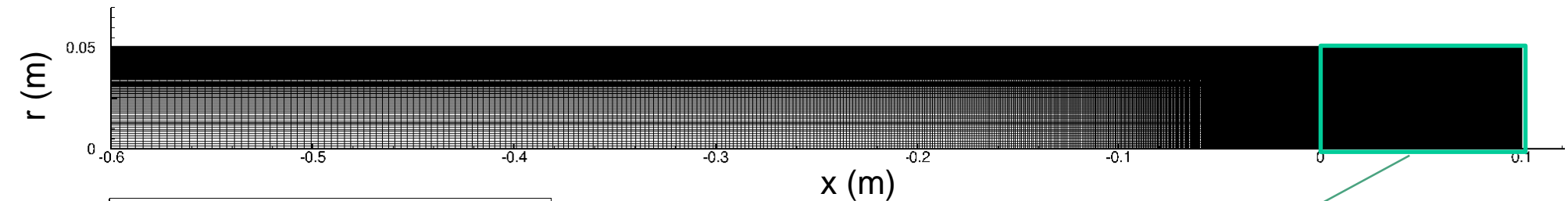
The whole frame is moved with a constant speed close to the shock-speed



Fluid Solver Results: US3D



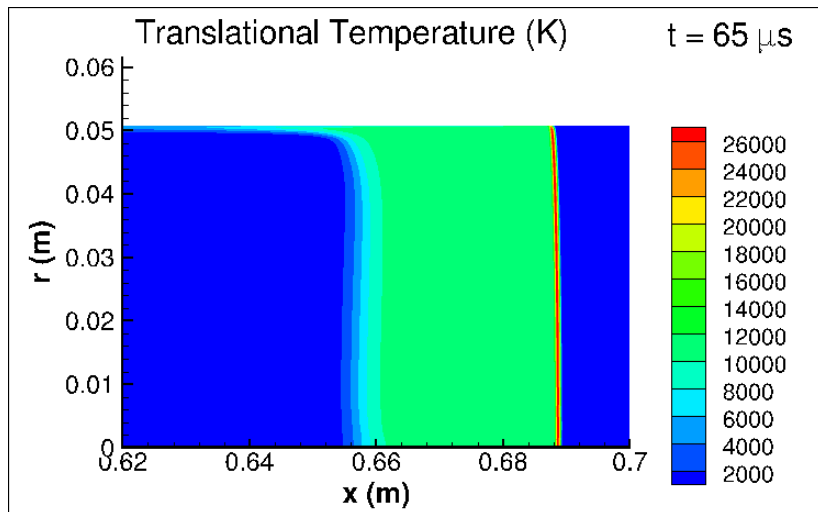
Early evolution of shock



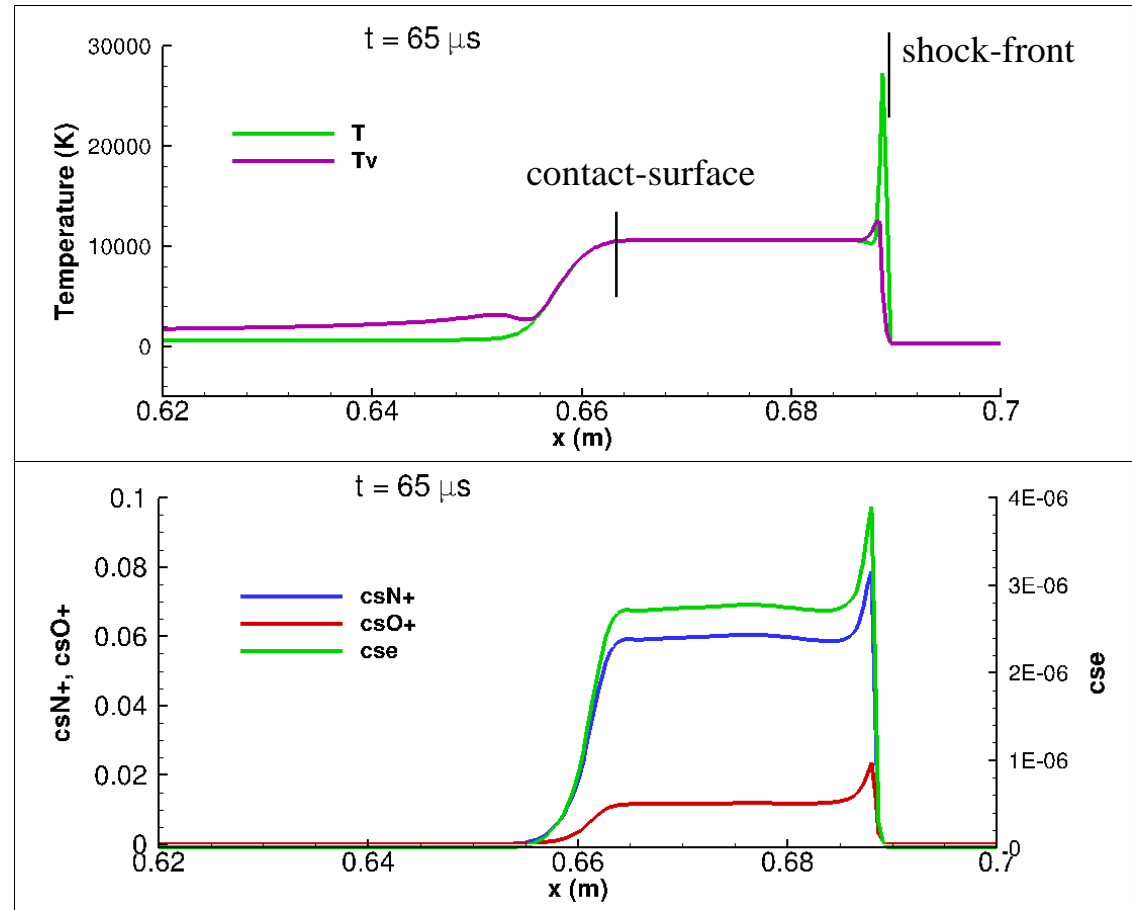
- Shock-deceleration profile consistent w/ EAST.
- Translational and Vibration-electronic modes relax with time.

Shock-deceleration is stronger in 2nd order flux-scheme

Flow-field at later time

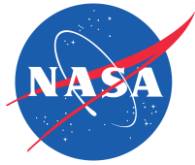


Centerline profiles

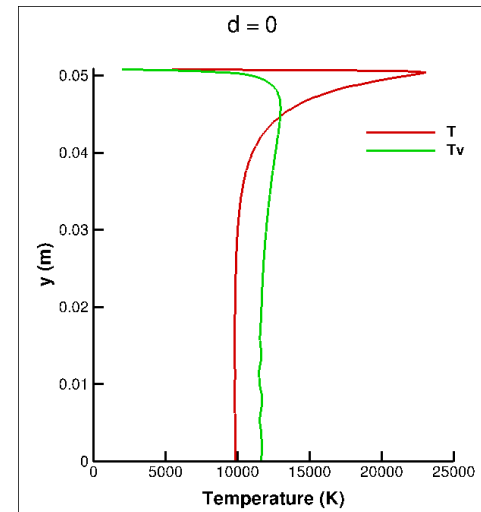
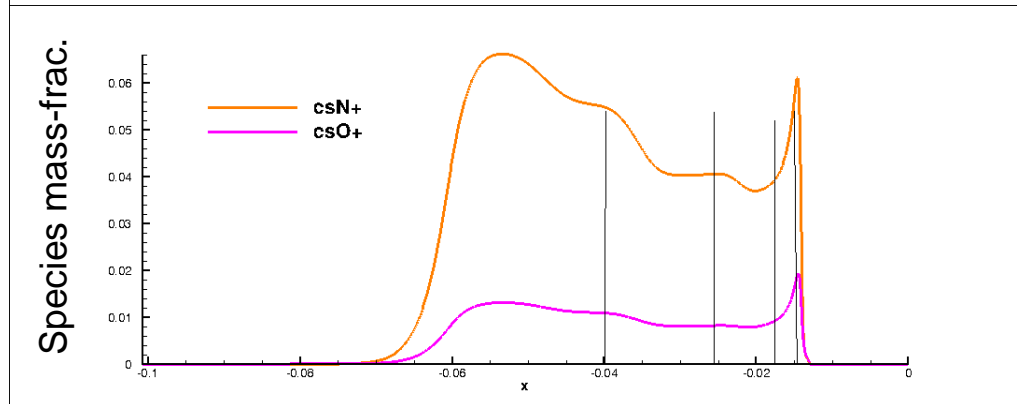
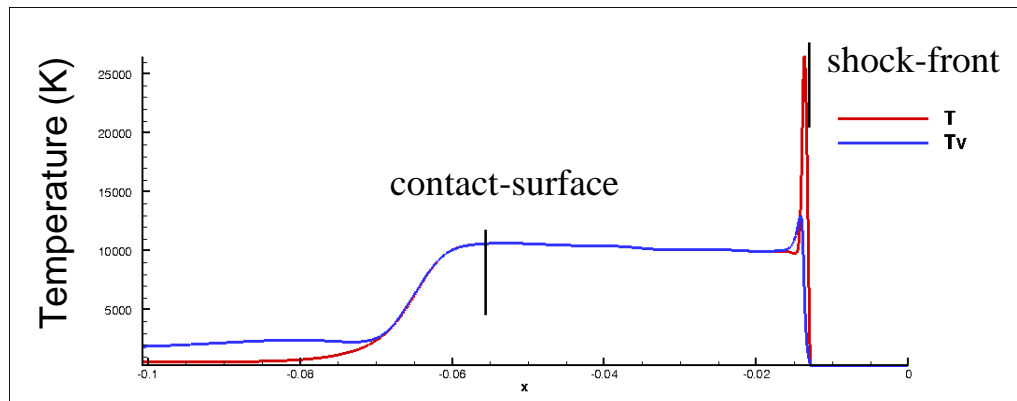
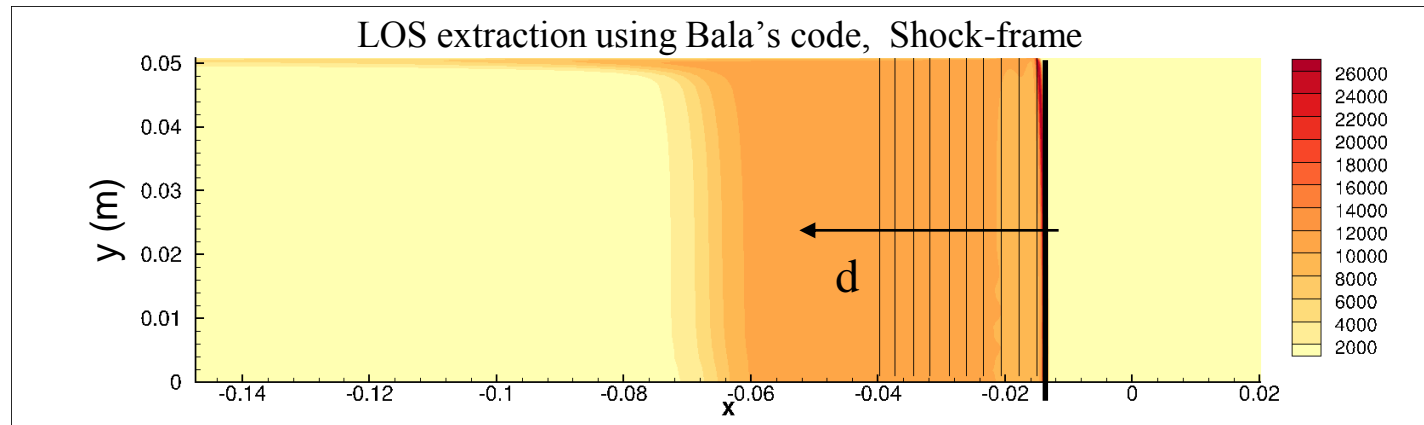


Axial-profiles are well-behaved near regions of strong gradients

Set-up for Radiation Calculations



- Shock reached at $\sim 1.29m$
- Shock-front is kept in the refined region by **changing** the frame-speed.



- Thermo-chemical equilibrium is not fully established.
- Radiation properties would be different than the measurements at the Test-section.



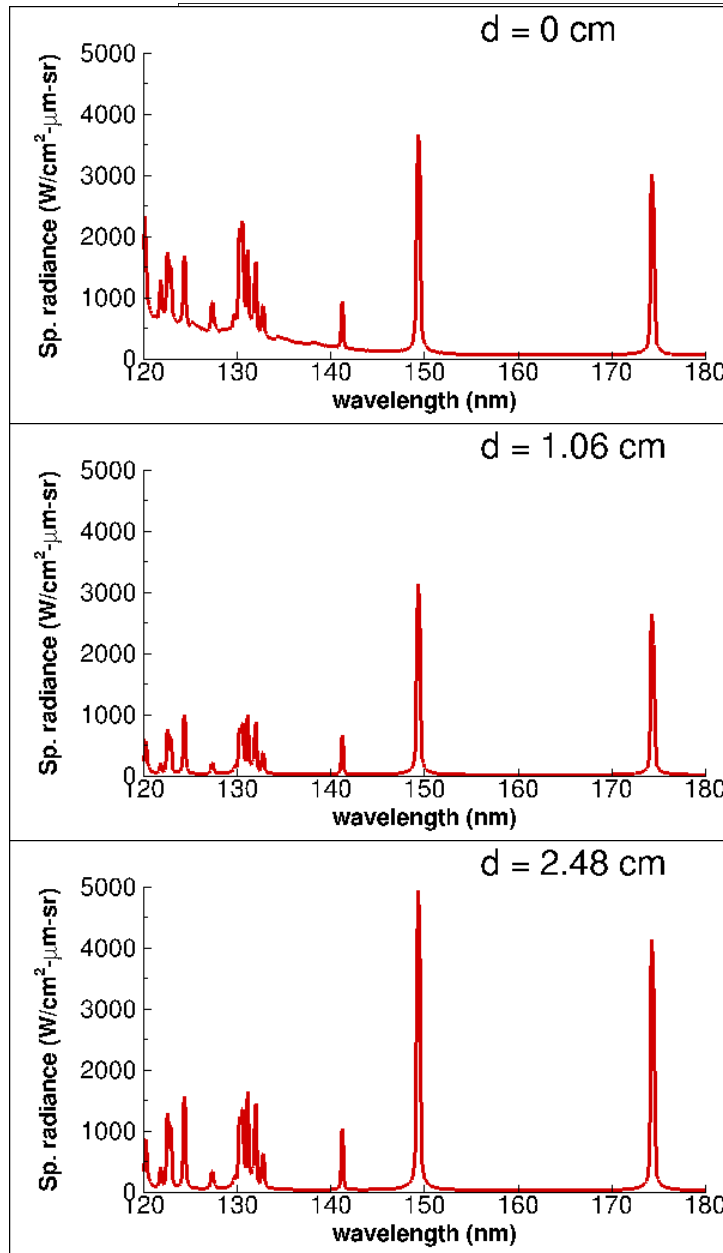
Radiation Solver Results: NEQAIR



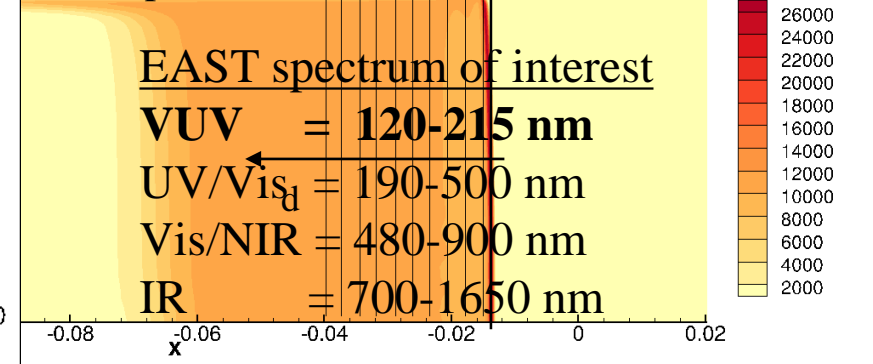
VUV Radiation



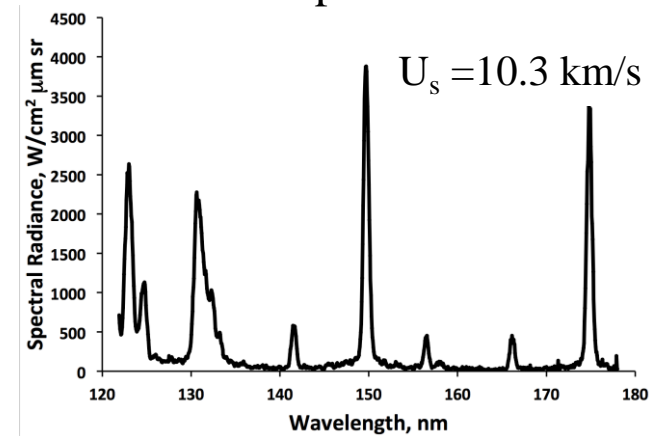
$U_s = 10 \text{ km/s}$



on Temperature contours, Shock-frame



experiment

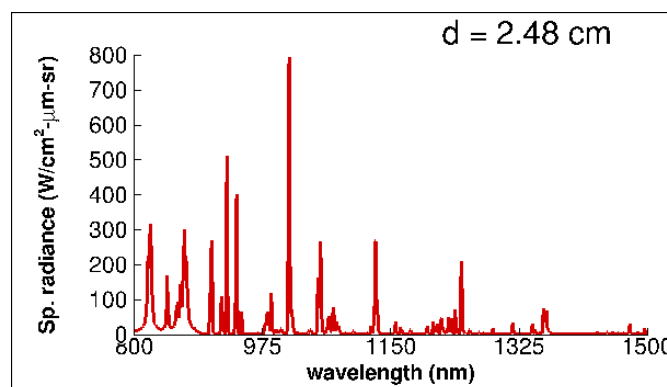
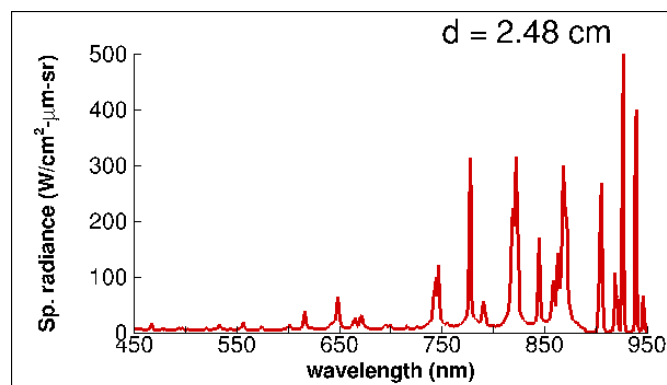
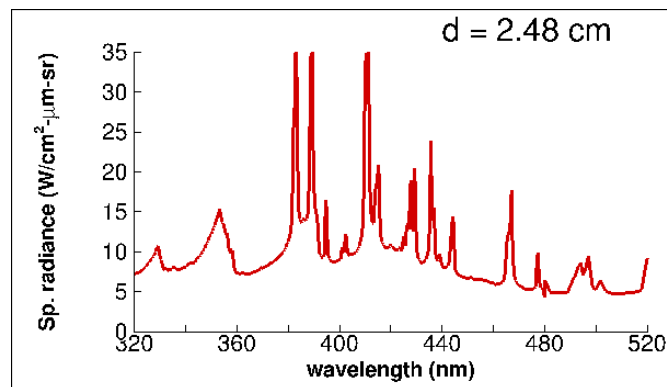
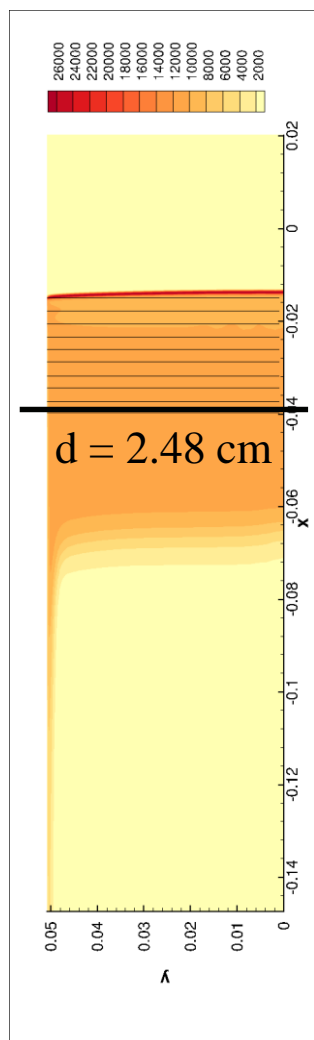


Qualitative behavior is similar.

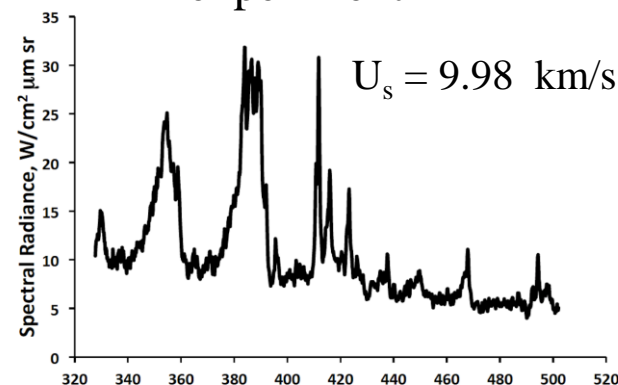
Radiation Spectra



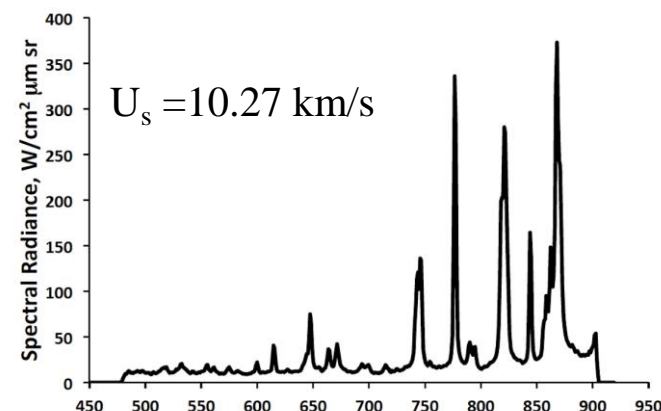
$U_s = 10.02$ km/s
 $P = 0.2$ Torr



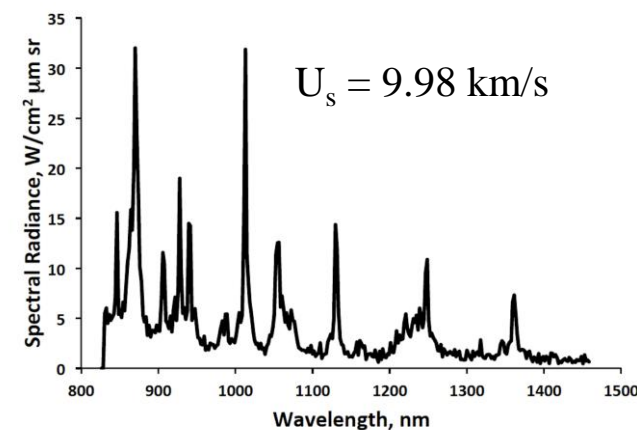
experiment



UV/Vis



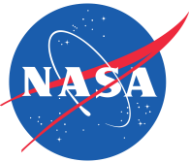
Vis/NIR



IR

(a) Equilibrium

Summary



Progress in Summer:

- Improved approach in US3D gives stable solution w/ real-gas effects.
(shock-front has to be kept in the refined region)
- Flow solution and Radiation profiles are consistent w/ test.

Path Forward:

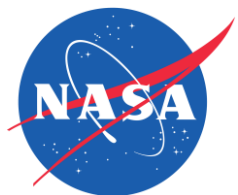
- Propagate the shock till test-section.
(Projected time: 14 days, 480 CPUs; 8 times cheaper than Kotov et. al.)
- Resolve BL features
- Include capability for variable frame-speed in US3D.
- Validate results w/ test-data.

Mentoring and Support

- Dr. A. Brandis, Dr. B. Cruden, Dr. D. Hash; (NASA Ames)
- Prof. G. V. Candler, Dr. I. Nompelis; (UMN)

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Questions?

